CALIFORNIA INSTITUTE OF TECHNOLOGY

Pasadena, California, 91125

SEMI-ANNUAL STATUS REPORT

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Grant NGR 05-002-160

"RESEARCH IN PARTICLES AND FIELDS"

for

1 October 1974 - 31 March 1975

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Coinvestigators

(NASA-CR-142956) RESEARCH IN PARTICLES AND FIELDS Semiannual Status Report, 1 Oct. 1974 - 31 Mar. 1975 (California Inst. of Tech.) 35 p HC $3.75 CSCL 03B

N75-25789

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The present report covers the research activities in Cosmic Rays and Theory of Particles and Fields in Space supported under NASA Grant NGR 05-002-160.*

The report is divided into sections which describe the various activities, followed by a bibliography.

1. Cosmic Rays (Vogt, Stone, and Mewaldt)

This group's research program is directed toward the investigation of the astrophysical aspects of cosmic radiation and of the radiation environment of the Earth by means of particle-detector systems flown on spacecraft and balloons. The main efforts of the group, which are supported partially or fully by this grant, have been directed toward the following two categories of experiments.

A. EXPERIMENTS ON NASA SPACECRAFT

1. An Electron/Isotope Spectrometer (EIS) Launched on IMP-7 on 22 September 1972 and on IMP-8 on 26 October 1973

This experiment is designed to measure the energy spectra of electrons and positrons(0.16 to ~6 MeV), and the differential energy spectra of the nuclear isotopes of hydrogen, helium, lithium, and beryllium (~2 to ~50 MeV/nucleon). In addition, it provides measurements of the isotopes of carbon, nitrogen, and oxygen from ~5 to ~15 MeV/nucleon.

* The NASA Technical Officer for this grant is Dr. A.G. Opp, NASA HQ., Physics and Astronomy Programs.

The measurements from this experiment supports studies of the origin, propagation, and solar modulation of galactic cosmic rays; the acceleration and propagation of solar flare particles, and the acceleration of charged particles within the magnetosphere.

Both the IMP-7 and IMP-8 instruments are completely functional, providing simultaneous measurements at two well separated locations. This combination of measurements should be particularly useful in the separation of spatial and temporal effects in studies of the interplanetary propagation of solar flare particles, in studies of the access of solar flare particles into the magnetotail, and in studies of local acceleration processes in the magnetotail.

The results of several studies of the isotopic composition of low energy cosmic rays were presented at the 2nd Cosmic Ray Isotope Symposium held at the University of New Hampshire in October 1974.

Using data from the IMP-7 EIS, we reported measurements of the isotopic composition of quiet time hydrogen and helium nuclei. These observations cover the energy intervals 5-29 MeV/nucleon for ^{2}H and 7-50 MeV/nucleon for ^{3}He. Measurements of these isotopes are important because their relative abundances should reflect the mean pathlength of primary ^{1}H and ^{4}He in the interstellar medium and the energy spectra of these nuclei in local interstellar space.

Examples of the hydrogen and helium mass spectra obtained are shown in Figures 1 and 2. Above ~ 20 MeV/nucleon, we observe well resolved abundances of both ^{2}H and ^{3}He. The separation of the ^{2}H and ^{1}H mass peaks, and the background level in the region of the ^{2}H peak, are significantly better than in previously reported measurements in this energy region, where there has, in the past, been some controversy about the ^{2}H abundance. Below ~10 MeV/nucleon we have obtained only upper limits to the ^{2}H and ^{3}He intensities. We find that the energy

spectra of ^1H, ^2H, and ^3He all fall rapidly with decreasing energy, giving $^2H/^1H$ and $^3He/^1H$ ratios that are essentially independent of energy. On the other hand, the measured ^4He spectrum was essentially flat from ~3 to ~ 40 MeV/nucleon and therefore the measured $^2H/^4He$, and $^3He/^4He$ ratios strongly energy dependent, with $^2H/^4He$ and $^3He/^4He$ less than ~ 2% at ~ 5-10 MeV/nucleon. We find that the ^1H, ^2H, and ^3He spectra are consistent with the $j = AT$ behavior expected from conventional solar modulation theories that include adiabatic deceleration, while the ^4He spectrum is anomalous, possibly because of a local source of ^4He. For this reason, we conclude that the $^2H/^4He$ ratio at 1 AU cannot be simply related to the interstellar abundances of these nuclei, as was conventionally assumed in the past. Interstellar propagation and solar modulation calculations are now underway to interpret these ^1H, ^2H, and ^3He spectra.

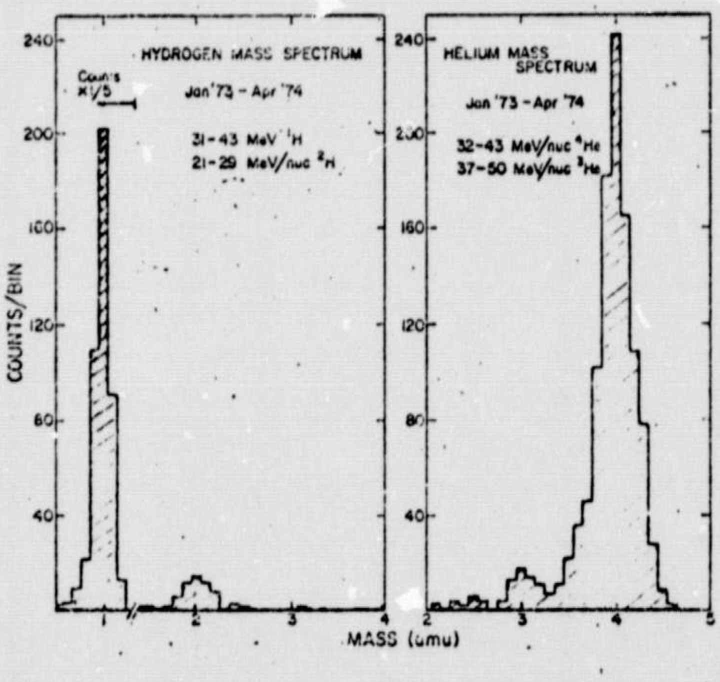

FIGURE 1

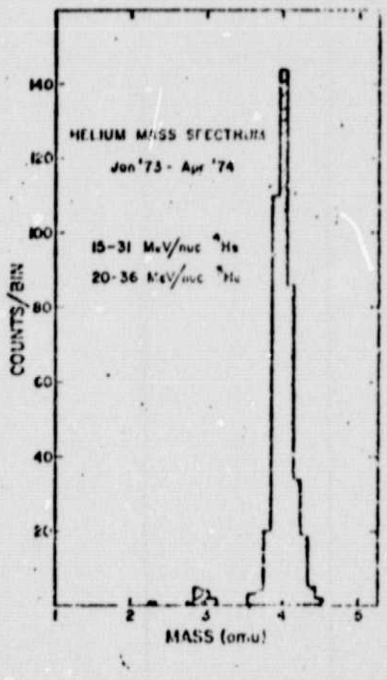

FIGURE 2

In a second paper at the Isotope Symposium, we reported the results of heavy ion calibrations of our spare flight telescope at the Berkeley 88" cyclotron (see Status Report for 1 April 1974 - 30 September 1974). these extensive calibrations we analyzed a total of ~ 10^6 individual events including isotopes of all elements with $1 \leq Z \leq 9$. Figure 3 shows an example of a ΔE vs residual energy plot for a small fraction of the data obtained. Separated tracks due to Li^6, Li^7, Li^8; Be^7, Be^9 and Be^{10}; and B^{10}, B^{11}, B^{12} are clearly visible. Figure 4, which shows examples of the mass histograms obtained, demonstrates the excellent isotopic resolution of the instrument. The deviation of some of the peaks from integer mass values is the result of inaccuracies due to use of conventional range-energy tables as discussed below. The resolution can be improved through calibrations.

Typical values for the measured mass resolution are $\sigma_m \simeq 0.2$ amu for Be^9 and Be^{10}, and $\sigma_m \simeq 0.35$ amu at O^{16}. These measured values agree well with the expected mass resolution based on the physical parameters of the detector system, giving us confidence in the calculational technique used to predict the response of the IMP-7 and -8 flight instruments.

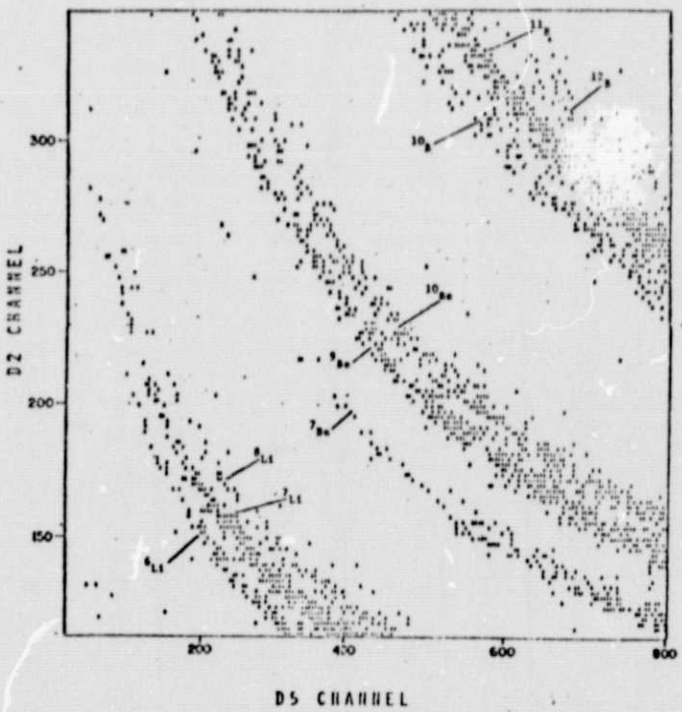

FIGURE 3

An important outcome of these heavy ion calibrations was the discovery that at the lowest energies measured ($\sim$ 5-10 MeV/nucleon), our use of conventional range-energy tables was not suitable to describe the response of the EIS to heavy ions. We found that the range-energy relations for heavy ions in silicon detectors did not scale exactly with Z^2/A from proton range-energy tables, even when electron pickup corrections were included. We found systematic deviations of up to ~1 amu in direct comparison with our calibration data resulting from a pure O^{16} beam. For this reason we have used our calibration data to develop empirical range-energy relations appropriate for our thin silicon solid-state detectors. The results of our heavy ion calibration work have had a direct and positive effect on the interpretation of our inflight measurements of the isotopic composition of the enhanced low energy fluxes of nitrogen and oxygen.

<u>Note</u>: Mass histograms were constructed using standard range-energy tables. The misalignment of the mass peaks with integer mass values is due to the use of these tables.

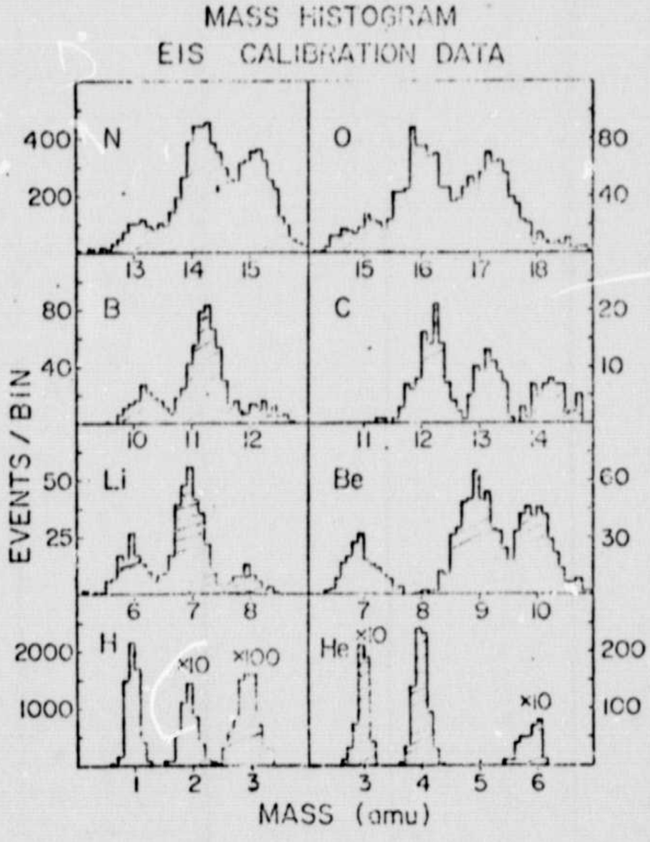

FIGURE 4

Figure 5 shows a dE/dx vs residual energy plot of our flight data for ~5-12 MeV/nucleon CNO nuclei, along with our calibrated tracks for ^{14}N and ^{16}O, and the tracks for a number of CNO isotopes as calculated from range-energy tables. Note that the calibrated ^{16}O track agrees with the oxygen flight data much better than the calculated tracks, especially at the lowest energies. Figure 6 compares the oxygen mass histograms of quiet time IMP-7 flight data that result from use of the calculated (= uncorrected) and calibrated (= corrected) tracks. The improvement is significant and obvious.

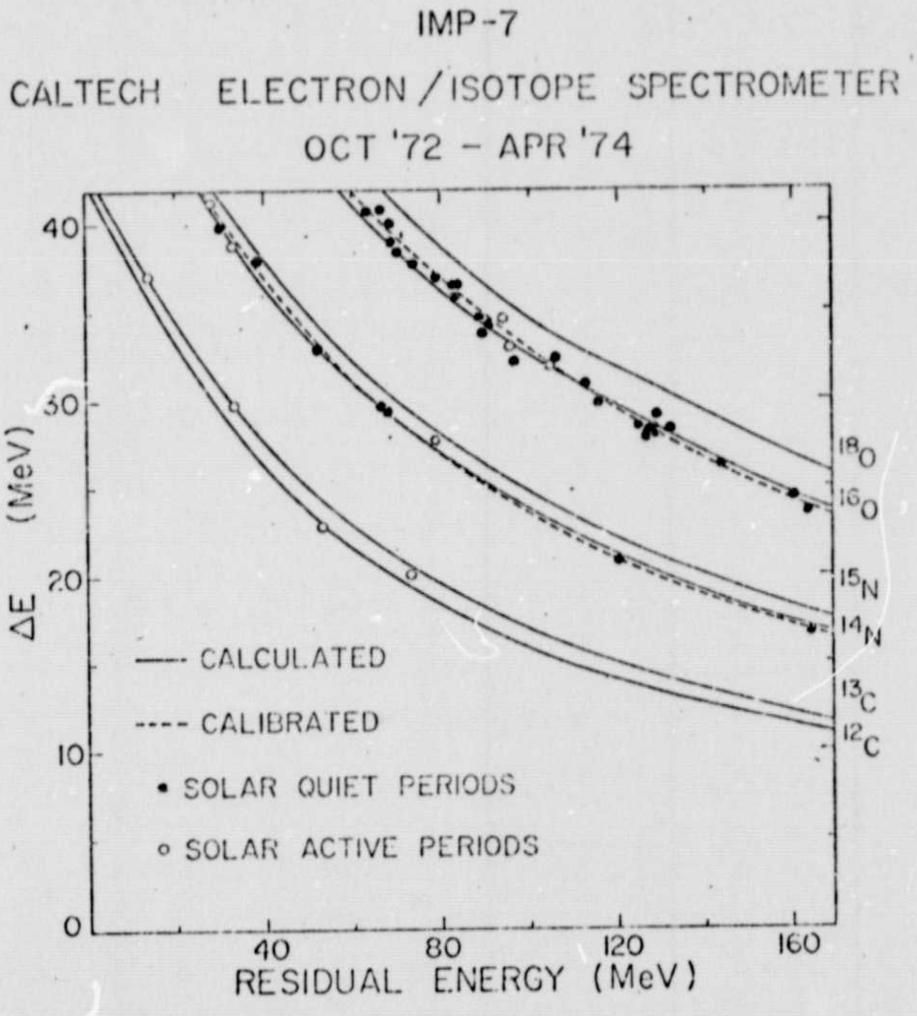

FIGURE 5

This refinement in our understanding of the EIS isotope response confirms our earlier conclusion (see Status Report 1 April 1974 - 30 September 1974) that ^{14}N and ^{16}O are the dominant isotopes in the low energy cosmic rays, and also results in a reduction in the upper limit value for the relative abundance of ^{17}O. The revised upper limit for the ^{17}O fraction, as reported at the New Hampshire conference, is $^{17}O/O \leq 0.09$ at the 84% confidence level. This work has demonstrated again the importance of detailed accelerator calibrations of low energy cosmic ray instruments.

Also reported at the isotope conference were the results of G.J. Hurford's Ph.D. thesis on the isotopic composition of hydrogen and helium nuclei in solar flares. This work was discussed in detail in the semi-annual report for the period 1 April 1974 - 30 September 1974.

At the 1975 annual meeting of the American Physical Society held in Anaheim in January, R.A. Mewaldt presented an invited paper entitled

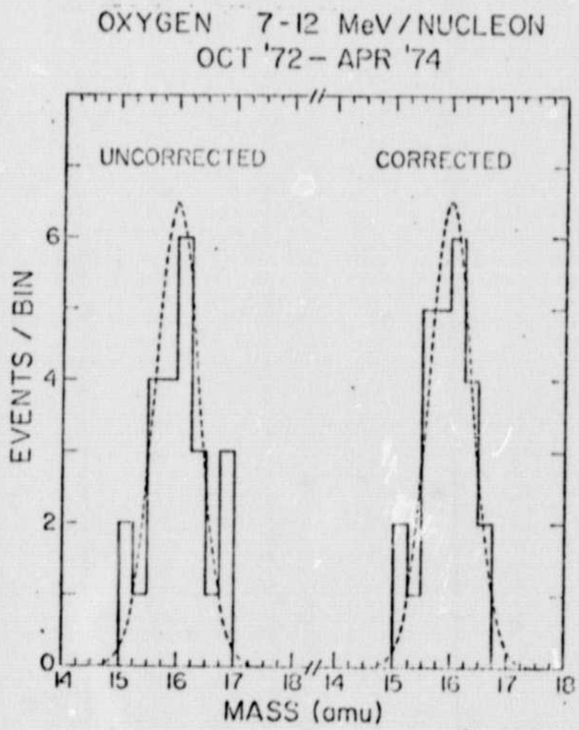

FIGURE 6

"The Anomalous Low Energy Cosmic Rays: Local or Interstellar?" In this talk he reviewed recent observations and interpretations of the enhanced fluxes of nitrogen and oxygen in low energy cosmic rays, as reported by this and other experimental groups.

2. A Heavy Nuclei Experiment (HNE) to be Launched on HEAO-C in 1979

The Heavy Nuclei Experiment (HNE) is a joint experiment involving this group and M.H. Israel, J. Klarmann (Washington University), W.R. Binns (McDonnell-Douglas), and C.J. Waddington (University of Minnesota). HNE is designed to measure the elemental abundances of relativistic high-Z cosmic ray nuclei ($17 \leq Z \leq 130$). The results of such measurements are of significance to the studies of nucleosynthesis and stellar structures, the existence of extreme transuranic nuclei, the origin of cosmic rays, and the physical properties of the interstellar medium.

The redesign of the instrument for HEAO-C has been completed to the extent necessary to provide the basis for a detailed cost estimate. Proposals for the hardware phase have been submitted to Marshall Space Flight Center in anticipation that intensive design and fabrication will begin in October 1976.

3. An Interstellar Cosmic Ray and Planetary Magnetospheres Experiment for the Mariner-Jupiter-Saturn (MJS) Missions

This experiment has been proposed jointly by this group and F.B. McDonald, B.J. Teegarden, and J.H. Trainor (Goddard Space Flight Center) and W.R. Webber (University of New Hampshire) and was selected as the Cosmic Ray Subsystem (CRS) for the MJS77 missions. The experiment is designed to measure the energy spectra, elemental and isotopic composition, and streaming patterns of galactic cosmic-ray nuclei from H to Fe over an energy range of 0.5 to 500 MeV/nucleon, and the energy spectra of electrons with 3 - 100 MeV. These measurements will be of particular importance to studies of stellar nucleosynthesis,

and of the origin, acceleration, and interstellar propagation of cosmic rays. Measurements of the energy spectra and composition of energetic particles trapped in the magnetospheres of Jupiter and (possibly) Saturn will be used to study their origin and relationship to other physical phenomena and parameters of these planets. Measurements of the intensity and directional characteristics of solar and galactic energetic particles as a function of heliocentric distance will be used for in situ studies of the interplanetary medium and its boundary with the interstellar medium.

Detailed design of the flight and ground support systems has been continued and fabrication has started. Full scale testing of solid-state detectors, using the grant supported SSD test and calibration facility (see Status Report 1 April 1974 - 30 September 1974), has begun. A review of the survival capability of the CRS in the Jovian environment was undertaken and reflected into the design.

4. A Heavy Isotope Spectometer Telescope (HIST) to be Flown on ISEE-C (Heliocentric)

HIST is designed to measure the isotopic abundances and energy spectra of solar and galactic cosmic rays for all elements from lithium to nickel ($3 \leq Z \leq 28$) over an energy range from several MeV/nucleon to several hundred MeV/nucleon. Such measurements are of importance to the study of the isotopic constitution of solar matter and of cosmic ray sources, the study on nucleosynthesis, questions of solar-system origin, studies of acceleration processes and studies of the life history of cosmic rays in the galaxy.

Project funding for hardware design and fabrication is presently scheduled for FY76. In preparation for that phase, a detailed experiment description has been written for distribution to potential hardware subcontractors. A request for proposal will be released in one month, with subcontractor selection scheduled for July 1975.

B. ACTIVITIES IN SUPPORT OF OR IN PREPARATION OF SPACECRAFT EXPERIMENTS

These activities generally embrace prototypes of experiments on existing or future NASA spacecraft or they complement and/or support such observations.

1. The High Energy Isotope Spectometer Telescope (HEIST)

HEIST is a balloon-borne detector system designed to provide high resolution isotopic measurements for cosmic ray nuclei with $3 \leq Z \leq 28$ in the energy interval $60 \leq E \leq 700$ MeV/nucleon, complementing the measurements which this group has been selected to make with the HIST instrument on ISEE-C.

The resolution of the heavier isotopes requires careful control and accurate knowledge of the various parameters of the system. Presently, twelve different sources of uncertainty are subject to careful laboratory measurements and numerical evaluation at the subsystem level. Upon completion of the individual test, the system will be assembled and tested at the Bevalac in order to further characterize the performance of the instrument. The Bevalac test will be designed not only as a calibration of the isotopic resolution of the instrument, but also as an evaluation of the individual contributions of the various sources of uncertainty to the overall mass resolution. These individual contributions can then be compared with those predicted from the subsystem tests. The results of two key subsystem tests are reviewed below as an indication of the approach being taken to evaluate the sources of uncertainty. For example, uncertainty in the detector thickness penetrated by a given particle is one of the twelve sources of uncertainty. The results of laboratory measurements of the CsI(Tℓ) detector thickness profile are described below.

Since the detectors are not perfectly planar, the thickness uncertainty is also related to the uncertainty in the location at which the particle penetrates the detector. Positional uncertainty also contributes to uncertainties of the angle of incidence,and hence the pathlength, of

the particle and to uncertainties in the light collection efficiency in the CsI(Tℓ) detectors. Laboratory measurements of the position resolution of the muli-wire proportional chambers (MWPC) are also described below.

It was necessary to develop large area, high-spatial resolution position-sensing devices in order to minimize the above uncertanties while maintaining a reasonably large geometrical factor. The MWPC design is based on that of Perez-Mendez at Lawrence Berkeley Laboratories. However, considerable development work was required in order to obtain the necessary spatial resolution over a large dynamic range ($3 \leq Z \leq 28$, rather than $Z = 1$ as in a high energy physics experiment).

The MWPC has multiple cathode and anode wires, with a cathode wire spacing of 2 mm. Each cathode wire is capacitatively coupled to a delay line. When an event occurs near the cathode wire coupled to the center of the delay line, the induced signal propagates toward both ends of the delay lines, arriving at the two ends simultaneously (zero time difference). For signals other than at the center, the finite time difference in the arrival time of the signal at the two ends provides a direct measure of the location of the event.

A full size, 0.5m x 0.5m chamber has been constructed and tested using fast timing electronics with nanosecond resolution which has been designed and fabricated in our laboratory for use in balloon instruments. The spatial linearity of the MWPC system was checked by using a collimated alpha particle source. The position of the source was under computer control, as was the acquisition of the time-difference data from the delay line. The measured mean time difference vs the source position is shown in Figure 7. The slope of the line is 15.3 ns/mm. As this data indicates, the source position can be interpolated between the cathode wires which are on 2 mm centers.

The uncertainty in the location of an individual event can be determined from Figure 8, which shows the distribution of the time differences for a fixed source position. The rms timing uncertainty of 4.8 ns corresponds to an rms spatial uncertainty of 0.31 mm.

The other essential element of HEIST is the stack of CsI (Tℓ) scintillators, which are 11" diameter disks of graduated thicknesses ranging from 3 to 17 mm. The thickness uncertainty of a given disk directly affects the mass resolution of the instrument. The design requirement is that the rms thickness uncertainty be $\sigma_t \leq 0.2\%$. Although the actual thickness can be accurately measured over the entire disk, the actual point of penetration of a particular particle will have an rms uncertainty of $\sigma_r = (\sigma_x^2 + \sigma_y^2)^{1/2} \approx \sqrt{2}\sigma_x$ where σ_x is obtained from Figure 8. The corresponding uncertainty σ_t in the thick-

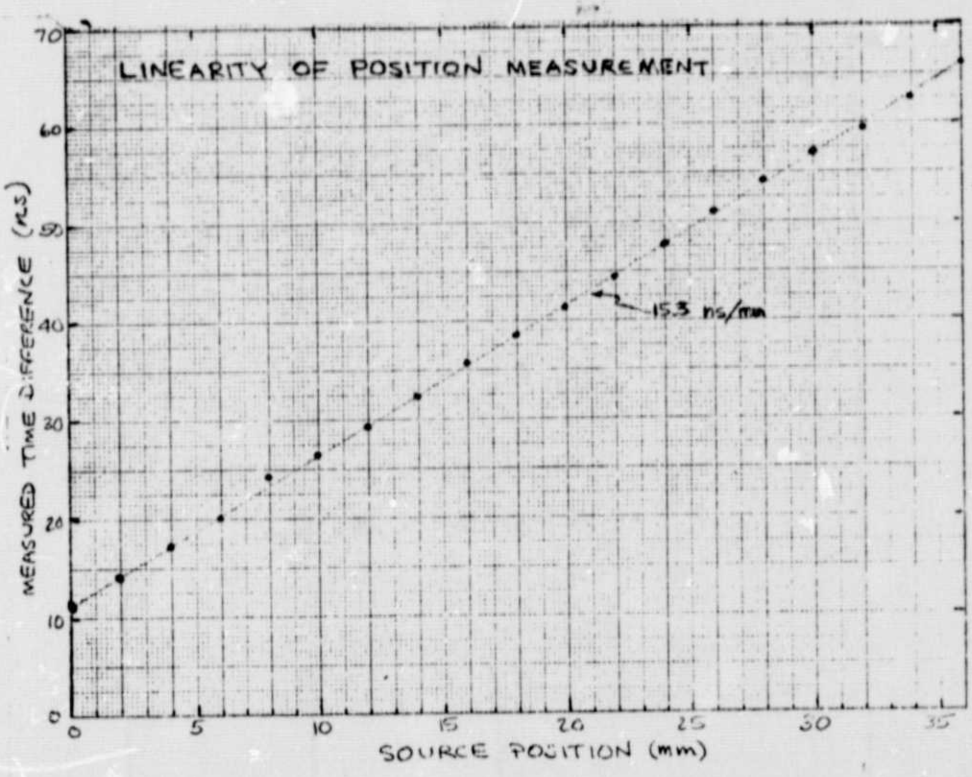

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FIGURE 7

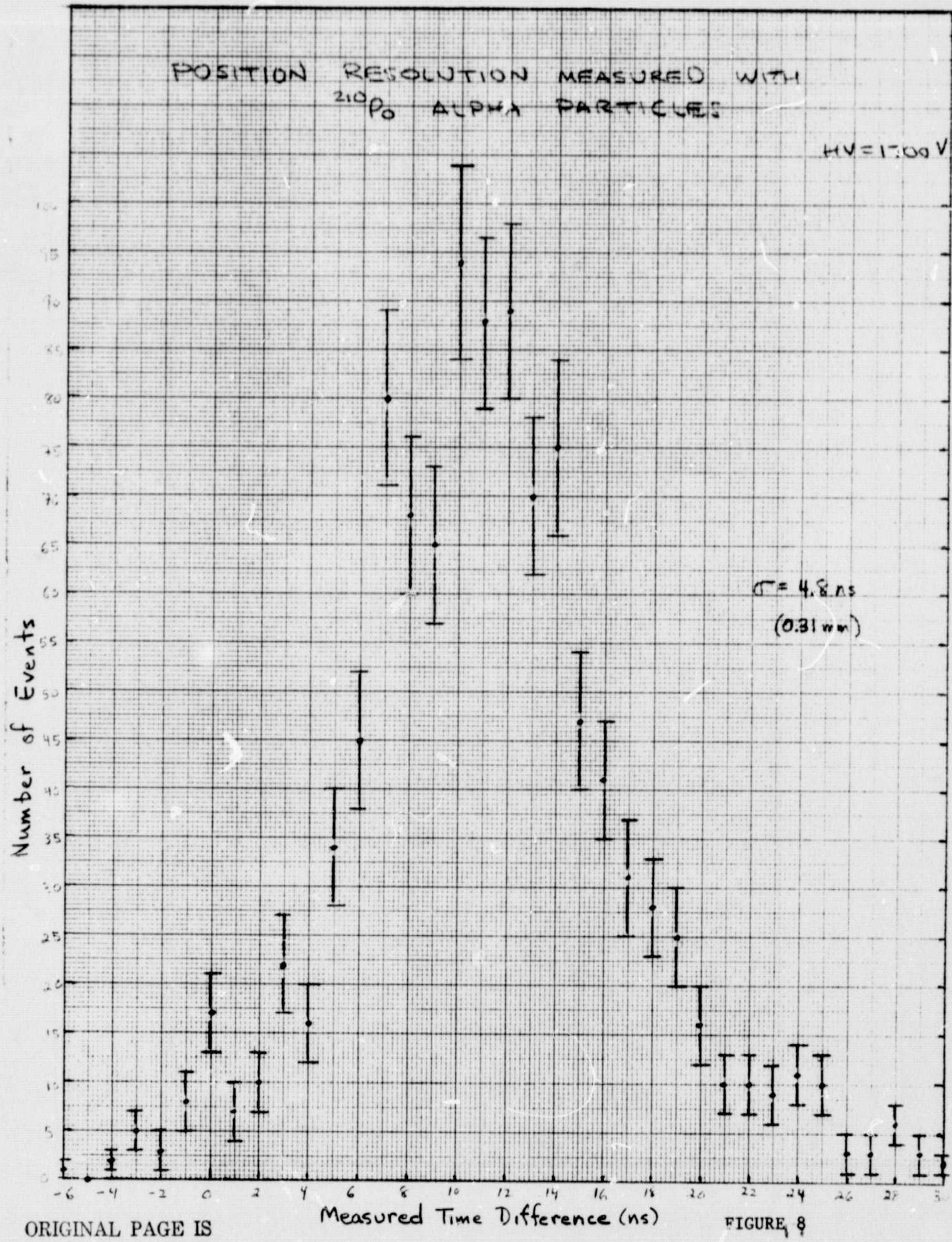

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FIGURE 8

ness depends on the gradient in the thickness profile, i.e., $\sigma_t \simeq \sigma_r\ \partial t/\partial r$. The $\sigma_t \lesssim 0.2\%$ combined with the above position uncertainty of $\sigma_r \sim 0.4$ mm, yields a requirement of $\partial t/\partial r \leq 0.5\%/\text{mm}$.

The thickness profiles were measured using γ-ray absorption. With adequate counting statistics, very small differences in absorber thickness can be determined. A typical thickness profile is illustrated in Figure 9 for a 3mm thick crystal. When compared to the contour spacing corresponding to 0.1%/mm, it is clear that $^{\partial t}/\partial r < 0.1\%$mm for all of the crystal area mapped. Thickness measurements near the crystal edges are not yet completed, but indications are that the requirement that $^{\partial t}/\partial r < 0.5\%/\text{mm}$ will be met.

2. Cosmic Ray Isotope Spectometers: The State of the Art

In an invited paper presented at the ESRO workshop on "Research Goals for Cosmic Ray Astophysics in the 1980's" Frascati, Italy, 24 October 1974, E.C. Stone reviewed the method for determining isotopic masses using dE/dx, Cerenkov, and total energy measurements. The following synopsis of that paper illustrates the present status of these methods with an indication of the expected improvements, including that expected from the Caltech Heavy Isotope Spectrometer Telescope (HIST) and the Caltech balloon-borne High Energy Isotope Spectrometer Telescope (HEIST).

A schematic (and simplified) illustration of the determination of the mass M of a cosmic ray nuclide with charge Z and kinetic energy E by using the dE/dx-E technique is shown in Figure 10. The particle penetrates a detector of thickness L, depositing ionization energy ΔE in that detector and depositing its residual energy E' in a second detector. For the purposes of an illustrative calculation, it is assumed that the range R of a particle with total kinetic energy E (where $E = E' + \Delta E$) is given by a power law expression. A similar expression is assumed for a

CRYSTAL THICKNESS VARIATIONS
FOR 3mm THICK CsI(Tl) CRYSTAL

THE THICKNESS VARIATION IS DEFINED TO BE ZERO AT THE CENTER OF THE CRYSTAL.

CONTOUR INTERVAL = 10 μm

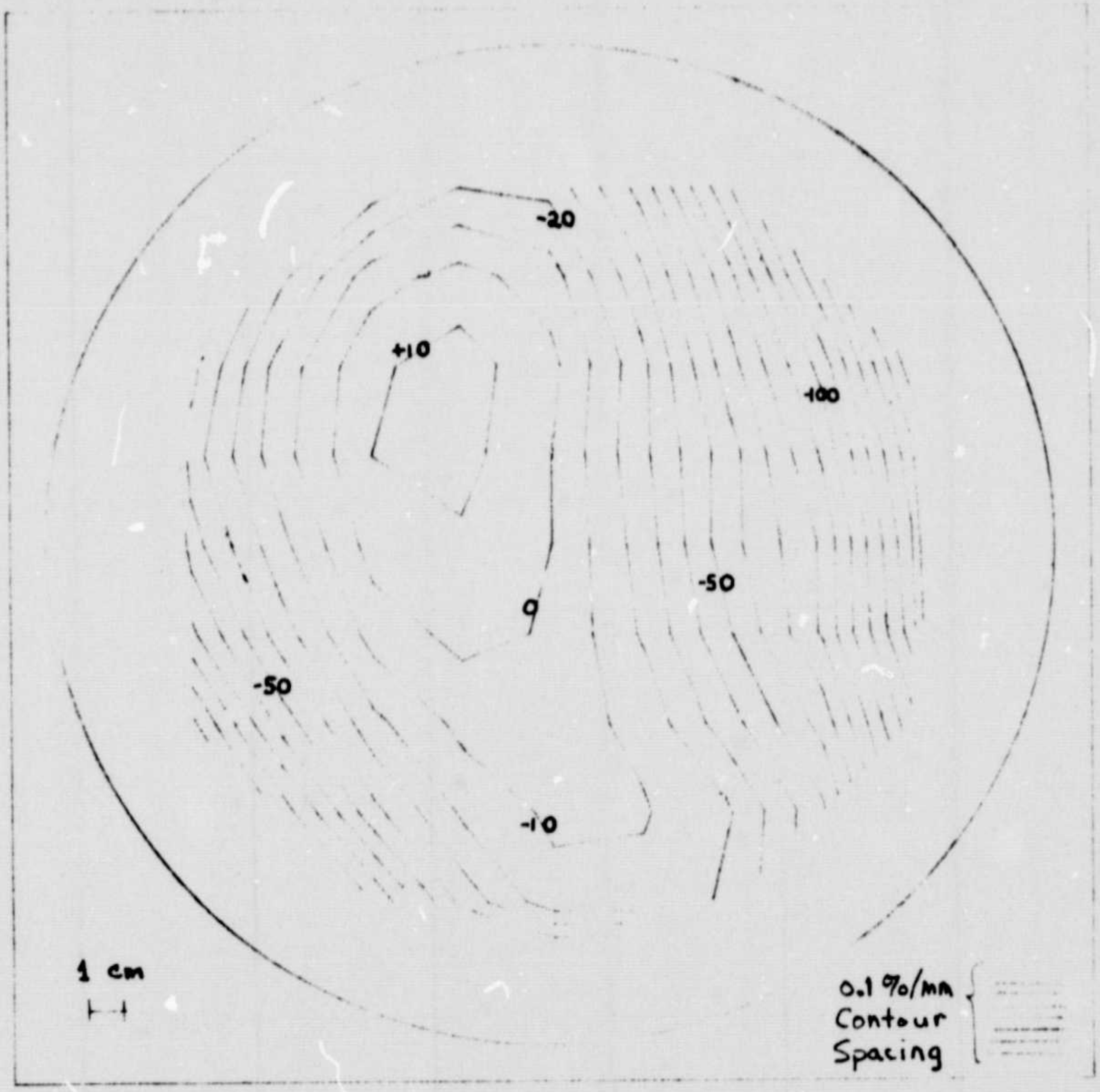

FIGURE 9

particle of range R-L and energy E'.

As shown, the two expressions can be solved for M. The expression for emphasizes the point that any uncertainties in ΔE (such as Landau fluctuations), E' (such as scintillator irregularities), L (such as unknown incidence angles), or in any of the other parameters will result in an uncertainty in the derived value for M.

The dE/dx-E mass identification technique is illustrated in Figure 11. The events shown are a small sample of $\sim 10^6$ events accumulated during the calibration of the Caltech Electron/Isotope Spectometer which is currently operational on the IMP-7 and IMP-8 spacecraft. In this case, ΔE was measured in a 50 μm thick silicon surface barrier detector and E' was measured in a 1 mm thick silicon detector. Tracks corresponding to ^{6}Li, ^{7}Li, ^{8}Li, ^{7}Be, ^{9}Be, ^{10}Be, ^{10}B, ^{11}B, and ^{12}B are evident. The mass resolution, which is dominated in this case by thickness non-uniformities in the 50μm detector is $\sigma_m \simeq 0.2$ amu. The calibration was done on the 88" cyclotron at the Lawrence Berkeley Laboratory.

dE/dX – E TECHNIQUE

ILLUSTRATIVE CALCULATION

$$R = \frac{KM}{Z^2}\left(\frac{E' + \Delta E}{M}\right)^a$$

$$R - L = \frac{KM}{Z^2}\left(\frac{E'}{M}\right)^a$$

SOLVE FOR M

$$M = \left(\frac{K}{LZ^2}\right)^{\frac{1}{a-1}}\left[(E' + \Delta E)^a - E'^a\right]^{\frac{1}{a-1}}$$

FIGURE 10

Typical mass resolutions reported for various recent satellite experiments using the dE/dx-E technique for the isotopes of elements up through Z = 8 are summarized in Figure 12. On the right there are four lines labeled 1:1, 2:1, 10:1, and 100:1 which are intended to indicate the mass resolution required to resolve adjacent isotopes with the specified relative abundances.

Also shown are typical mass resolutions which analysis indicates can be expected for different versions of the dE/dx-E technique. The disk detector systems will be able to resolve adjacent isotopes with Z ≤ 8. The use of multiple ΔE measurements and curved detectors will permit the resolution of adjacent isotopes up to Z ≈ 14. Finally, the use of position sensing as planned, for example, for the Caltech Heavy Isotope Spectrometer Telescope on ISEE-C, should provide isotopic resolution up through Z ≈ 28.

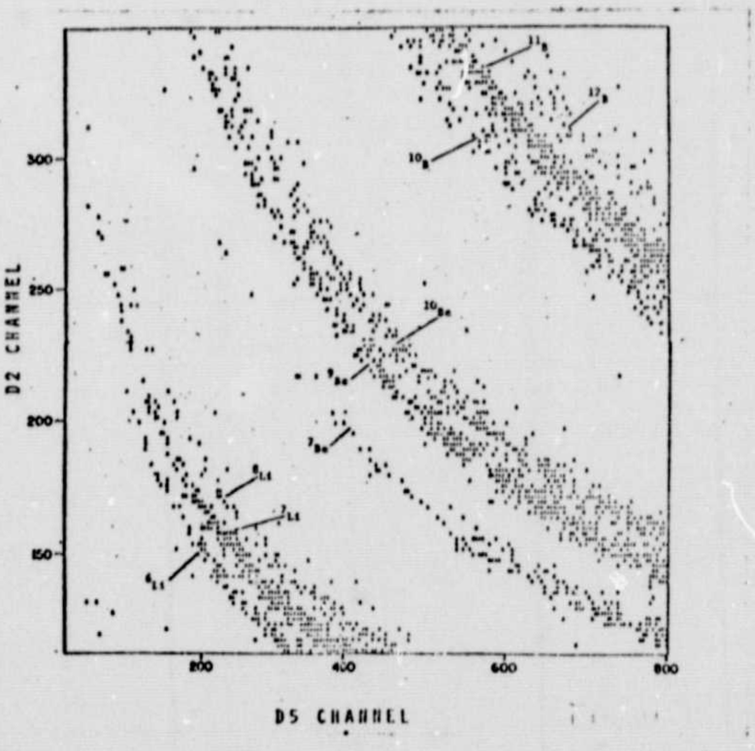

FIGURE 11

At somewhat higher energies, the $\check{C} \times E$ method of mass determination is useful. As shown in Figure 13, a cosmic ray nuclide (total kinetic energy E, mass M, charge Z, velocity βc) penetrates a Čerenkov radiator (thickness L, refractive index N) and stops in a detector which measures the energy E. For illustration, the ΔE in the Čerenkov radiator is neglected. The expression for the Čerenkov signal $\check{C}$ and the kinetic energy signal E are shown, where $\gamma = (1-\beta^2)^{-1/2}$. These two expressions can be solved for M as shown. The expression for M emphasizes that any uncertainty in E (such as due to scintillator resolution), $\check{C}$ (photo-electron statistics), K (variations in $\check{C}$ light collection), and L will result in an uncertainty in M.

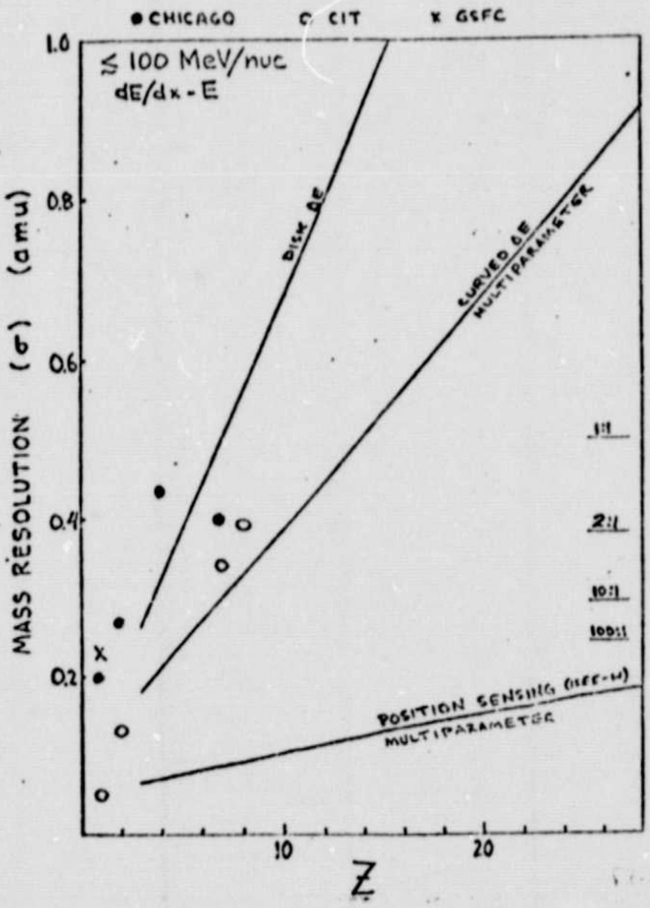

FIGURE 12

An analysis of the expected mass resolution for ^{56}Fe is shown in Figure 14. The upper solid curve corresponds to what is probably possible with the current techniques. For comparison, the mass resolution obtained by the University of New Hampshire group several years ago is shown. Separation of adjacent isotopes of Fe will require significant instrumental improvements as indicated by the line labeled "Future ?".

The dashed lines indicate the fraction of Fe events which do not suffer inelastic nuclear collision in the process of stopping in the E detector. Approximately 50%, 30% and 20% of the 400 MeV/nuc nuclei would interact in plastic, Si, and CsI detectors, resulting not only in a reduced detection efficiency, but producing presently unknown background effects. The evaluation of such systematic background effects

$\check{C} \times E$ TECHNIQUE

ILLUSTRATIVE CALCULATION
(NEGLECT ΔE IN L)

$$\check{C} = KLZ^2 \left(1 - \beta_t^2/\beta^2\right)$$

$$E = (\gamma - 1)\, Mc^2$$

WHERE

$$\beta_t = 1/N$$

SOLVE FOR M

$$M = \frac{E}{\left[\left\{\dfrac{1 - \check{C}/KLZ^2}{1 - \check{C}/KLZ^2 - \beta_t^2}\right\}^{1/2} - 1\right] c^2}$$

FIGURE 13

will require careful calibration. Those events (~1%) suffering single neutron stripping may be particularly troublesome.

Typical mass resolutions reported at ~100 MeV/nucleon by a number of groups using a variety of stopping-particle techniques is summarized in Figure 15. Except for the Kiel results which were obtained during an accelerator calibration, all of these results were obtained with balloon instruments. The upper dashed line indicates the expected mass resolution for the $\check{C}$ x E technique with current technology. The lower dashed curve indicates the expected resolution for the Caltech large area balloon-borne HEIST. Also shown is the expected resolution of the Berkeley multi-element silicon detector telescope which will be on ISEE (Heliocentric).

From these considerations, it seems reasonable to suggest that by 1980 small satellite experiments should have adequate mass resolution to provide clean information on the more abundant isotopes at energies E $\lesssim$500 MeV/nucleon. Large area balloon instruments can also provide useful isotopic information with reasonable event statistics. Thus,

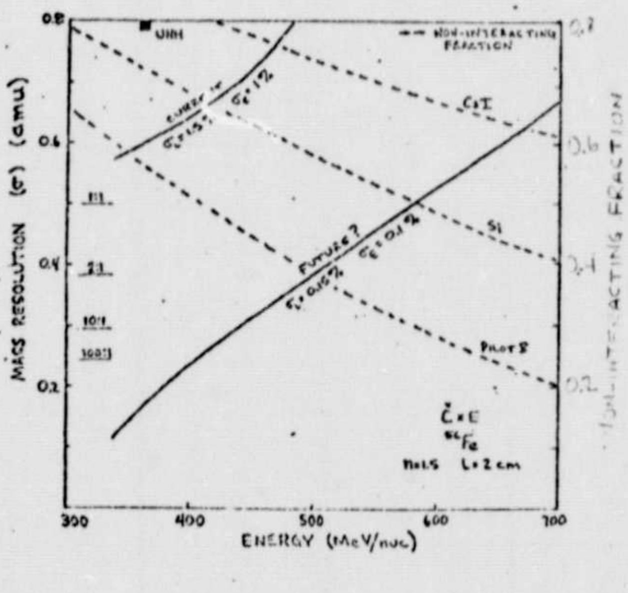

FIGURE 14

by 1980 we should have high quality information on the more abundant isotopes, but similar results on the rarer, and in certain instances very interesting, isotopes may have to wait for larger, more precise spectrometers on spacecraft in the 1980's.

3. Other Activities

E.C. Stone is serving as NASA's Project Scientist for the MJS77 Mariner-Jupiter-Saturn missions. He participated at the ESRO workshop on "Research Goals for Cosmic Ray Astrophysics in the 1980's", Frascati, Italy, 24 October 1974.

R.E. Vogt served as a member of the following NASA advisory committees or working groups: Physical Sciences Committee (PSC, NASA HQ, OSS), High Energy Astrophysics Working Group (NASA HQ., SA), and Jupiter-Uranus Science Advisory Committee (USAC, NASA HQ., SL). A

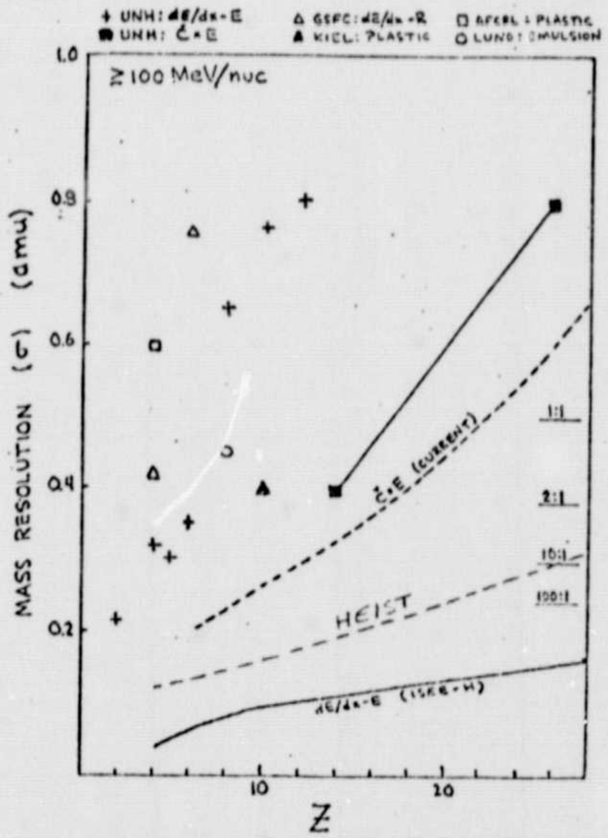

FIGURE 15

paper: "Particles and Fields in the Outer Solar System" by R.E. Vogt and G. Siscoe was published in ICARUS, 24, 333, 1975.

II. Theory of Particles and Fields in Space (L. Davis)

A. PIONEER 11 ENCOUNTER WITH JUPITER

Davis was substantially involved in the activities of the Vector Helium Magnetometer team before, during, and after the Pioneer 11 encounter with Jupiter. Before encouter, computer programs were prepared that would allow rapid analysis of the quicklook magnetometer data. During encounter, these programs provided the trajectory data needed for all parts of this analysis, produced provisional offset dipole and spherical harmonic models of the inner magnetosphere, and produced an extrapolation of the field to the planet's surface. Later, as more and better data became available, similar but more reliable analyses were carried out.

B. COMPARISON OF PIONEER 10 AND PIONEER 11 RESULTS

A series of offset dipole models were developed as shown in Table 1 below. These included D_2 and D_4, which are direct fits of the observations made by Pioneers 10 and 11, respectively, to the offset dipole model, and a series of offset dipoles deduced indirectly from spherical harmonic analyses using data taken over various radial ranges and using varying numbers of harmonics extending in some cases as far as interior source octupole and exterior source quadrupole terms. The procedure for deriving an offset dipole representation was taken, with some corrections of details, from Chapman and Bartels. From these analyses it appeared that the representations of the field deduced from the Pioneer 11 data were quite similar to those deduced from the Pioneer 10 data. There were small differences between the two sets, but it could not be determined whether they were due to a real change of the field with time or whether they were due to artifacts of the analysis process. Because the data were taken along different trajectories, apparent differences would be produced by any plasma currents in the radial range from which data were used, by any higher order terms not included in a particular analysis, or by any errors in trajectory, spacecraft attitude, or magnetometer data.

Table 1.

Eccentric dipole parameters computed from spherical harmonic analysis coefficients.

Ident.	Pion.	Range R_J	Wt. (r^n) n =	Int. Coefs.	Ext. Coefs.	Dipole Postion: Cartesian Z_o	X_o	Y_o	Spherical Polar R	LAT	LONG III	Dipole Moment $\lvert M\rvert$	TILT	LONG III	RMS Resid. (γ)
Case 1	11	< 8	3/2	15	8	.0103	-.1107	-.0076	.1115	5.32	176.0	4.192	9.94	227.2	58
2	11	< 12	3/2	15	8	.0125	-.1027	-.0044	.1036	6.94	177.5	4.229	9.87	226.8	38
5	11	< 6	3/2	15	8	.0129	-.1018	-.0043	.1027	7.21	177.6	4.234	9.97	226.0	132
6	11	< 3	3/2	15	8	.0194	-.0692	-.0021	.0719	15.68	178.2	4.322	9.53	220.9	452
9	11	< 6	1	15	8	.0160	-.1026	-.0008	.1038	8.89	179.6	4.234	9.95	224.2	438
JOB 303	11	< 8	3/2	15	3	.0105	-.1128	-.0065	.1135	5.30	176.7	4.188	10.04	226.0	67
JOB 303	11	< 8	3/2	15	0	.0094	-.1152	-.0042	.1157	4.64	177.2	4.217	10.65	229.2	106
JOB 303	11	< 8	3/2	8	8	.0013	-.0990	-.0057	.0991	-0.76	176.7	4.221	10.95	229.6	188
JOB 303	11	< 8	3/2	8	0	.0025	-.1038	-.0021	.1039	1.37	178.8	4.224	11.00	229.4	211
D_4	11	< 6	3	-	-	.009	-.100	.001	.101	5.12	185.7	4.225	10.7[illegible]	230.9	-
M15-2;1	10	< 13	1	8	8	.0427	-.0806	-.0985	.1342	18.55	129.3	4.411	10.67	225.8	34
M15-2;1	10	< 13	1	8	3	.0283	-.0966	-.0563	.1154	14.19	149.8	4.403	10.10	228.0	44
M15-2;1	10	< 13	1	8	0	.0240	-.1251	-.0202	.1289	10.71	170.8	3.985	10.51	232.8	81
M15-2;5	10	< 6	1	8	8	.0431	-.0747	-.0969	.1297	19.42	127.6	4.401	11.22	225.2	27
M15-2;5	10	< 6	1	8	3	.0348	-.0801	-.0971	.1306	15.46	129.5	4.409	10.56	225.2	34
M15-2;5	10	< 6	1	8	0	.0260	-.10[illegible]	-.0384	.1166	12.90	160.3	4.168	10.39	229.3	65
D_2	10	< 6	3	-	-	.030	-.105	-.008	.110	15.90	176.6	4.000	10.62	222.1	-

Note: D_2 and D_4 are the offset dipole models obtained by direct analysis; not as a secondary result of an analysis in terms of spherical harmonic coefficients. In determining these coefficients, the error (or residual) in fit at each point is given the weight r^n, where r is the radial distance and n is tabulated, and the weighted RMS residual is minimized. To characterize the interior and exterior sources, three coefficients are used for a dipole source only, eight if a quadrupole is added, and 15 if an octupole is also added.

It does not appear that a definitive, accurate description of the magnetic field of Jupiter within, say, 10 R_J of the center will emerge from these two flybys but it does seem likely that any of the analyses with small residuals will provide a representation that will be useful and valid for many purposes.

C. EXOTIC APPLICATIONS

Stimulated by correspondence with M.M. Nieto and A.S. Goldhaber, Davis modified the spherical harmonic analysis of the Pioneer 10 magnetometer data to include the changes required in the formulas describing vacuum magnetic fields that would be required if photons should have a very small but non-zero rest mass. This would cause a change in the structure of magnetic fields that would be apparent over distances inversely proportional to the mass. The results showed no evidence that the rest mass was not zero. If interpreted in the normal way, the results gave an upper limit to the mass of 8×10^{-49} grams, corresponding to a length of 5×10^{10} cm, which is better by a factor of 5 than the corresponding limits deduced from a similar analysis of the earth's magnetic field.

However, a skeptic can well argue that unexplained systematic effects are observed in the analysis of Jupiter's inner magnetosphere, and in most similar analyses of other large scale fields. These could, if we are unlucky, diabolically conceal a much larger photon mass. He could also point out that unless something is very wrong with the theories and observations of the galactic magnetic field, the limiting rest mass of the photon should be pushed down several more orders of magnitude by a similar argument applied to that field. Nevertheless, those physicists who are interested in the possibility that photons might have a finite mass seem keenly interested in this analysis of Jupiter's innner magnetosphere.

D. THEORY OF WAVE PROPAGATION THROUGH TURBULENT PLASMA

Under the supervision of Jokipii, L.C. Lee completed several papers and a thesis on the theory and astrophysical applications of the propagation of electromagnetic waves through turbulent plasma. A unified theory was developed which clarified and extended previous less systematic approaches by a number

of authors. Although Jokipii's primary location was the University of Arizona in Tucson, until this thesis was completed in January, he continued to supervise Mr. Lee's research, to receive support for this from NGR 05-002-160, and to hold an appointment at the California Institute of Technology.

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